

# **SANDIA REPORT**

SAND2002-3778

Unlimited Release

Printed November 2002

# **Neutron Contribution to CaF<sub>2</sub>: Mn Thermoluminescent Dosimeter Response in Mixed (n/γ) Field Environments**

K. Russell DePriest

Prepared by  
Sandia National Laboratories  
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,  
a Lockheed Martin Company, for the United States Department of  
Energy under Contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.



**Sandia National Laboratories**

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

**NOTICE:** This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from  
U.S. Department of Energy  
Office of Scientific and Technical Information  
P.O. Box 62  
Oak Ridge, TN 37831

Telephone: (865)576-8401  
Facsimile: (865)576-5728  
E-Mail: [reports@adonis.osti.gov](mailto:reports@adonis.osti.gov)  
Online ordering: <http://www.doe.gov/bridge>

Available to the public from  
U.S. Department of Commerce  
National Technical Information Service  
5285 Port Royal Rd  
Springfield, VA 22161

Telephone: (800)553-6847  
Facsimile: (703)605-6900  
E-Mail: [orders@ntis.fedworld.gov](mailto:orders@ntis.fedworld.gov)  
Online order: <http://www.ntis.gov/ordering.htm>



## **Neutron Contribution to CaF<sub>2</sub>:Mn Thermoluminescent Dosimeter Response in Mixed (n/γ) Field Environments**

K. Russell DePriest  
Applied Nuclear Technologies  
Sandia National Laboratories  
P.O. Box 5800  
Albuquerque, NM 87185-1146

### **Abstract**

Thermoluminescent dosimeters (TLDs), particularly CaF<sub>2</sub>:Mn, are often used as photon dosimeters in mixed (n/γ) field environments. In these mixed field environments, it is desirable to separate the photon response of a dosimeter from the neutron response. For passive dosimeters that measure an integral response, such as TLDs, the separation of the two components must be performed by post-experiment analysis because the TLD reading system cannot distinguish between photon and neutron produced response. Using a model of an aluminum-equilibrated TLD-400 chip, a systematic effort has been made to analytically determine the various components that contribute to the neutron response of a TLD reading. The calculations were performed for five measured reactor neutron spectra and one theoretical thermal neutron spectrum. The five measured reactor spectra all have dosimetry quality experimental values for aluminum-equilibrated TLD-400 chips. Calculations were used to determined the percentage of the total TLD response produced by neutron interactions in the TLD and aluminum equilibrator. These calculations will aid the Sandia National Laboratories-Radiation Metrology Laboratory (SNL-RML) in the interpretation of the uncertainty for TLD dosimetry measurements in the mixed field environments produced by SNL reactor facilities.

**LEFT BLANK INTENTIONALLY**

## CONTENTS

<b>EXECUTIVE SUMMARY.....</b>	8
<b>1. INTRODUCTION .....</b>	9
<b>2. GEOMETRY AND MATERIAL COMPOSITION .....</b>	10
<b>3. CONTRIBUTIONS FROM VARIOUS COMPONENTS.....</b>	12
<b>3.1 Direct Neutron Kerma.....</b>	12
<b>3.2 Secondary <math>\gamma</math>Dose .....</b>	13
<b>3.3 Dose from TLD Activation Products.....</b>	14
<b>3.4 Dose From Aluminum Activation Products.....</b>	16
<b>3.5 Dose From Charged Particles Produced By High Energy Neutrons .....</b>	16
<b>4. SUMMARY.....</b>	17
<b>5. CONCLUSIONS .....</b>	21
<b>6. REFERENCES .....</b>	22
<b>APPENDIX A – MCNP4C3 Sample Input Deck for Neutron Kerma and Secondary <math>\gamma</math> Kerma – ACF9 Neutron Spectrum.....</b>	23
<b>APPENDIX B – MCNP4C3 Sample Input Deck for TLD Activation Dose from <math>\beta</math>-Decay – <math>^{20}\text{F}</math> .....</b>	31
<b>APPENDIX C – MCNP4C3 Sample Input Deck for TLD Activation Dose from Delayed <math>\gamma</math>'s After <math>\beta</math>-Decay – <math>^{20}\text{F}</math> .....</b>	32
<b>APPENDIX D – MCNP4C3 Sample Input Deck for TLD Activation Dose from Internal Bremsstrahlung After <math>\beta</math>-Decay – <math>^{20}\text{F}</math>.....</b>	33
<b>APPENDIX E – MCNP4C3 Sample Input Deck for Aluminum Activation Dose from <math>\beta</math>-Decay – <math>^{28}\text{Al} .....</math></b>	34
<b>APPENDIX F – MCNP4C3 Sample Input Deck for Aluminum Activation Dose from Delayed <math>\gamma</math>'s After <math>\beta</math>-Decay – <math>^{28}\text{Al} .....</math></b>	35
<b>APPENDIX G – MCNP4C3 Sample Input Deck for TLD Activation Dose from Internal Bremsstrahlung After <math>\beta</math>-Decay – <math>^{28}\text{Al} .....</math></b>	36

## TABLES

<b>Table 1:</b> Typical Al6061 Aluminum Alloy Composition .....	<b>11</b>
<b>Table 2:</b> Typical TLD-400 (CaF <sub>2</sub> :Mn) Composition.....	<b>12</b>
<b>Table 3:</b> Direct and Effective Neutron Kerma in TLD-400 .....	<b>13</b>
<b>Table 4:</b> Secondary $\gamma$ Dose in CaF <sub>2</sub> :Mn TLDs .....	<b>14</b>
<b>Table 5:</b> Activation Product Dose From CaF <sub>2</sub> :Mn TLDs.....	<b>15</b>
<b>Table 6:</b> Activation Product Dose From Aluminum Equilibrator ....	<b>16</b>
<b>Table 7:</b> Charged Particle Dose from Aluminum Equilibrator.....	<b>17</b>
<b>Table 8:</b> Summary Table for Neutron Contributions to CaF <sub>2</sub> :Mn TLD Dose .....	<b>18</b>
<b>Table 9:</b> Summary of ACF9 Dosimetry Shot.....	<b>19</b>
<b>Table 10:</b> Summary of SPR3CC Dosimetry Shot .....	<b>19</b>
<b>Table 11:</b> Summary of WB7 Dosimetry Shot .....	<b>20</b>
<b>Table 12:</b> Summary of SPR_80a3 Dosimetry Shot .....	<b>20</b>
<b>Table 13:</b> Summary of FRECIIp6 Dosimetry Shot.....	<b>21</b>

## **FIGURES**

<b>Figure 1: Differential Number Spectra for the 6 Neutron Environments.</b> .....	<b>10</b>
<b>Figure 2: Lethargy Plot for the 6 Neutron Environments.</b> .....	<b>10</b>
<b>Figure 3: The Effective Neutron Kerma for CaF<sub>2</sub>:Mn TLDs.</b> .....	<b>13</b>
<b>Figure 4: Schematic of <sup>19</sup>O β-decay process.</b> .....	<b>15</b>

## **EXECUTIVE SUMMARY**

Thermoluminescent dosimeters (TLDs), particularly CaF<sub>2</sub>:Mn, are often used as photon dosimeters in mixed (n/γ) field environments. It has always been assumed that the neutron contribution to the dosimeter response was a small portion of the total. As the quantification of uncertainties in dose measurements becomes more urgent, there is a need to quantify the neutron component of the TLD response for the primary environments that customers use at Sandia National Laboratories (SNL) reactor facilities. The separation of the n/γ components must be performed by post-experiment analysis because the TLD reading system cannot distinguish between photon and neutron produced response. Using a model of an aluminum-equilibrated TLD-400 chip, a systematic effort has been made to analytically determine the various components that contribute to the neutron response of a TLD reading. The calculations were performed for five measured reactor neutron spectra and one theoretical thermal neutron spectrum. The five measured reactor spectra all have dosimetry quality experimental values for aluminum-equilibrated TLD-400 chips. The calculations were used to determine (*a posteriori*) the percentage of the total TLD response produced by neutron interactions in the TLD and aluminum equilibrator. For all but one of the reactor environments, the neutron component of the TLD response falls within the 5-12% uncertainty in the reading of the TLD crystal. These calculations will aid the SNL-Radiation Metrology Laboratory (SNL-RML) in the interpretation of the uncertainty for TLD photon dosimetry measurements in the mixed field environments produced by SNL reactor facilities.

## 1. INTRODUCTION

The response of CaF<sub>2</sub>:Mn thermoluminescent dosimeters (TLD) due to the neutron component of a mixed (n/γ) field environment is difficult to separate from the response that is attributable to the photon dose. In a systematic manner, an effort has been made to determine the various components that contribute to the neutron response of a TLD reading. The contributors identified for an aluminum equilibrated CaF<sub>2</sub>:Mn TLD in this process are given by the following list: (1) the direct neutron kerma within the TLD; (2) the dose from secondary γ's produced by reactions in both the aluminum equilibrator and the TLD material; (3) the dose contribution from the activation products created in the TLD material; (4) the dose contribution for the activation products created in the aluminum equilibrator; and (5) the dose from charged particles produced by high energy neutron reactions in the aluminum equilibrator.

Six separate neutron fields were considered in the evaluation of each of the different contributors to the neutron response. These reactor fields consist of a pool-type reactor cavity (ACF9), a hard spectrum from the cavity of a fast burst reactor (SPR3CC), a moderated spectrum representative of a water bucket in a pool-type cavity (WB7), a leakage spectrum from a fast burst reactor (SPR\_80a3), and an extremely moderated spectrum representative of a polyethylene bucket in a pool-type reactor (FRECIIP6). These five reactor fields are described in Reference [Gr94]. The final spectrum was a theoretical Maxwellian thermal neutron beam at a temperature of 20° C. The six spectra are displayed in Figures 1-2. Figure 1 is a standard plot of the differential number spectra (dN/dE) while Figure 2 is a lethargy plot (dE/dE) where equal areas under the curve represent equal numbers of neutrons. Figure 2 demonstrates the considerable diversity of neutron spectra that can be produced within the SNL reactor facilities. It also shows that it would be difficult to assign a reliable value for the neutron contribution to a CaF<sub>2</sub>:Mn TLD response for an unknown neutron spectrum because the neutron energy spectrum determines both the kerma and the activation products produced in the TLD.

The five measured reactor spectra all have dosimetry quality experimental values of the total response for aluminum-equilibrated TLD-400 chips in these fields. The calculations were used to determine (*a posteriori*) the percentage of the total TLD response produced by neutron interactions in the TLD and aluminum equilibrator. The Maxwellian thermal calculation was included to assess the effect of a pure thermal neutron beam on the overall TLD response, but there are no experimental values for comparison to these results at the present time. These calculations will aid the Sandia National Laboratories-Radiation Metrology Laboratory (SNL-RML) in the quantification of the uncertainty for TLD dosimetry measurements in the mixed field environments produced by SNL reactor facilities.

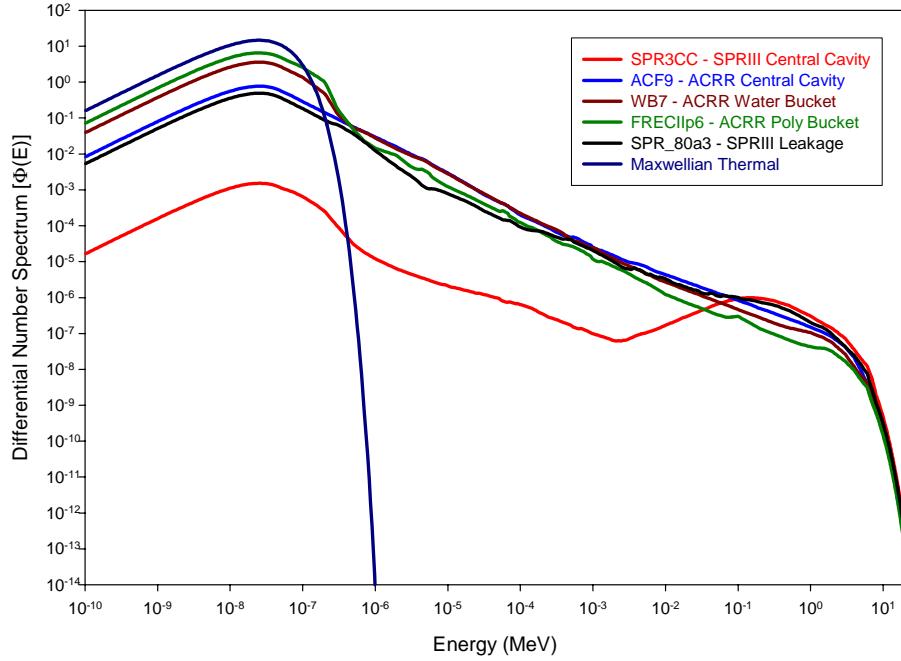


Figure 1: Differential Number Spectra for the 6 Neutron Environments.

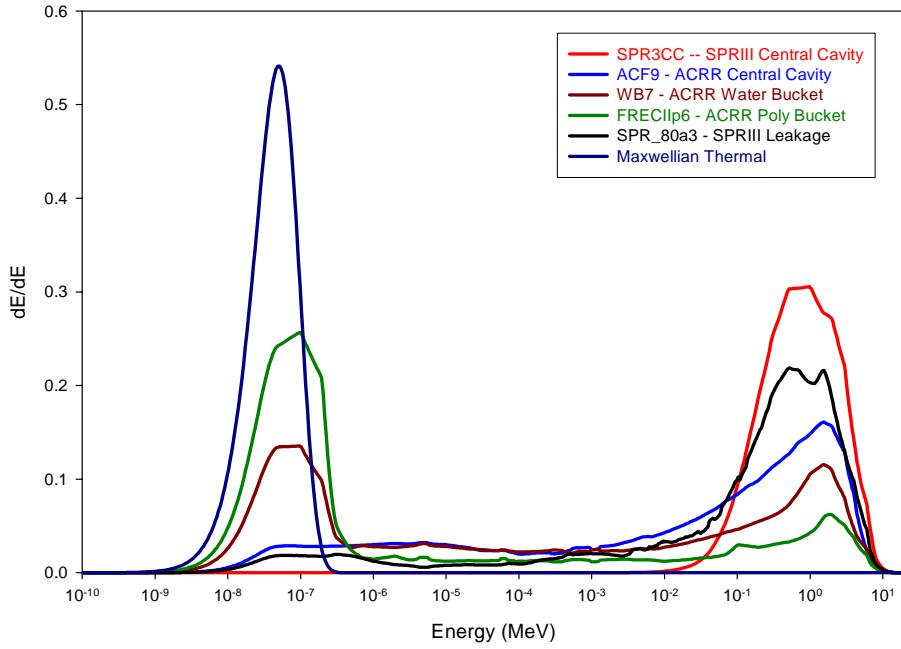


Figure 2: Lethargy Plot for the 6 Neutron Environments.

## 2. GEOMETRY AND MATERIAL COMPOSITION

A nominal SNL-RML aluminum-equilibrated TLD-400 chip was modeled. Both the aluminum equilibrator and the TLD-400 chip are represented as rectangular boxes in the model. A cavity is created in the aluminum equilibrator to accommodate the TLD-400 chip. The dimensions for

aluminum equilibrator are 0.8 cm x 0.8 cm x 0.5461 cm. The dimensions of the TLD-400 chip are 0.3 cm x 0.3 cm x 0.0889 cm. The total volume of the equilibrator is 0.341503 cm<sup>3</sup> while the TLD chip has a volume of 8.001x10<sup>-3</sup> cm<sup>3</sup>.

The aluminum equilibrator was assumed to be composed of the Al6061 alloy of aluminum. A typical composition for the Al6061 aluminum alloy is found in Table 1. The composition of the TLD-400 is CaF<sub>2</sub> doped with Mn to provide the thermoluminescent centers or “traps.” The weight percent of Mn for typical TLD-400 chips was determined by neutron activation analysis (NAA) performed at the SNL-RML. The Ca and F weight percentages were then determined by stoichiometric calculations. Table 2 shows the results of the NAA and the stoichiometric calculations of the material composition of CaF<sub>2</sub>:Mn TLD-400 chips. The density of the aluminum was assumed to be 2.71 g/cm<sup>3</sup>. The density of the CaF<sub>2</sub>:Mn chip was assumed to be 3.10 g/cm<sup>3</sup>.

Table 1: Typical Al6061 Aluminum Alloy Composition

<b>Element</b>	<b>Weight Percent (%)</b>	<b>Isotopes</b>	<b>Relative Abundance</b>
Silicon	0.60	<sup>28</sup> Si	0.9227
		<sup>29</sup> Si	0.0468
		<sup>30</sup> Si	0.0305
Manganese	0.15	<sup>55</sup> Mn	1.0000
Copper	0.27	<sup>63</sup> Cu	0.6910
		<sup>65</sup> Cu	0.3090
Magnesium	1.00	<sup>24</sup> Mg	0.7899
		<sup>25</sup> Mg	0.1000
		<sup>26</sup> Mg	0.1101
Titanium	0.15	<sup>46</sup> Ti	0.0800
		<sup>47</sup> Ti	0.0750
		<sup>48</sup> Ti	0.7370
		<sup>49</sup> Ti	0.0550
		<sup>50</sup> Ti	0.0530
Zinc	0.25	<sup>64</sup> Zn	0.4890
		<sup>66</sup> Zn	0.2780
		<sup>67</sup> Zn	0.0410
		<sup>68</sup> Zn	0.1860
		<sup>70</sup> Zn	0.0062
Chromium	0.20	<sup>50</sup> Cr	0.0435
		<sup>52</sup> Cr	0.8379
		<sup>53</sup> Cr	0.0950
		<sup>54</sup> Cr	0.0236
Iron	0.70	<sup>54</sup> Fe	0.0584
		<sup>56</sup> Fe	0.9168
		<sup>57</sup> Fe	0.0217
		<sup>58</sup> Fe	0.0031
Aluminum	96.68	<sup>27</sup> Al	1.0000

Table 2: Typical TLD-400 ( $\text{CaF}_2:\text{Mn}$ ) Composition

<b>Element</b>	<b>Weight Percent (%)</b>	<b>Isotopes</b>	<b>Relative Abundance</b>
Calcium	50.46	$^{40}\text{Ca}$	0.96940
		$^{42}\text{Ca}$	0.00650
		$^{43}\text{Ca}$	0.00140
		$^{44}\text{Ca}$	0.02080
		$^{48}\text{Ca}$	0.00190
Fluorine	47.84	$^{19}\text{F}$	1.00000
Manganese	1.70	$^{55}\text{Mn}$	1.00000

### 3. CONTRIBUTIONS FROM VARIOUS COMPONENTS

#### 3.1 Direct Neutron Kerma

In a mixed field environment, neutron interactions produce charged particles that deposit energy directly in the dosimeter material. The neutron kerma is determined by calculation and is equivalent to the absorbed dose when charged particle equilibrium (CPE) has been established. Using an MCNP4C2 [Br00] model of an aluminum-equilibrated TLD-400 chip, the neutron kerma was calculated using the internal MCNP kerma response for the TLD material. In using the kerma for the calculations, the escape of charged particles produced in the TLD material was neglected. This approximation was deemed valid based on the range of the protons and  $\alpha$ -particles produced in the TLD material. Since the range of the charged particles produced in the volume is small compared to the dimensions of the TLD-400 chip, the amount of energy of the charged particles leaving the volume is much smaller than the total energy deposited by those charged particles. Thus, the calculated kerma was assumed to be equal to the absorbed neutron dose. Although these charged particles are neglected in the TLD calculation, the energy deposited by the charged particles produced in the aluminum equilibrator is calculated below. This calculation is included because the energy deposited by the charged particles produced in the equilibrator and transported into the TLD is unaccounted for in any of the other calculations.

The calculated kerma corresponds to the actual energy deposited within the TLD by the neutrons in the spectra that were examined. The TLD, however, does not respond to the neutron ionization with the same efficiency as it does to photon irradiation. The neutron ionization is produced by intermediate neutron-induced charged particles and recoiling nuclei. The charged particles have a high linear energy transfer (LET), and high LET ionization is less efficient in populating the thermoluminescent traps that are emptied during the heating in a normal TLD reading. The efficiency of neutron ionization in populating the traps is dependent upon the energy of the neutrons because the LET changes rapidly for the spectra of neutron-induced charged particles and the recoiling nuclei. Thus, an energy-dependent effective neutron kerma in the TLD material was added as an external response for the MCNP calculation. The energy-dependent effective neutron kerma for  $\text{CaF}_2:\text{Mn}$  was a composite of the response from Henninger response [He82] at high energies and Rinard response [Ri79] at low energies. The transition between the two functions begins at  $1.3125\text{E+04}$  eV and concludes at  $1.0750\text{E+03}$  eV. The transition used an average of the two responses and gave each response equal weight. The two functions and the composite are displayed below in Figure 3. The kerma and effective kerma for

all the neutron spectra are found in Table 3. [NOTE: The number of digits in the tables below do not represent the precision of the quantities. The digits are given to aid in reproducibility and to provide an auditable record of the origin of the numbers.]

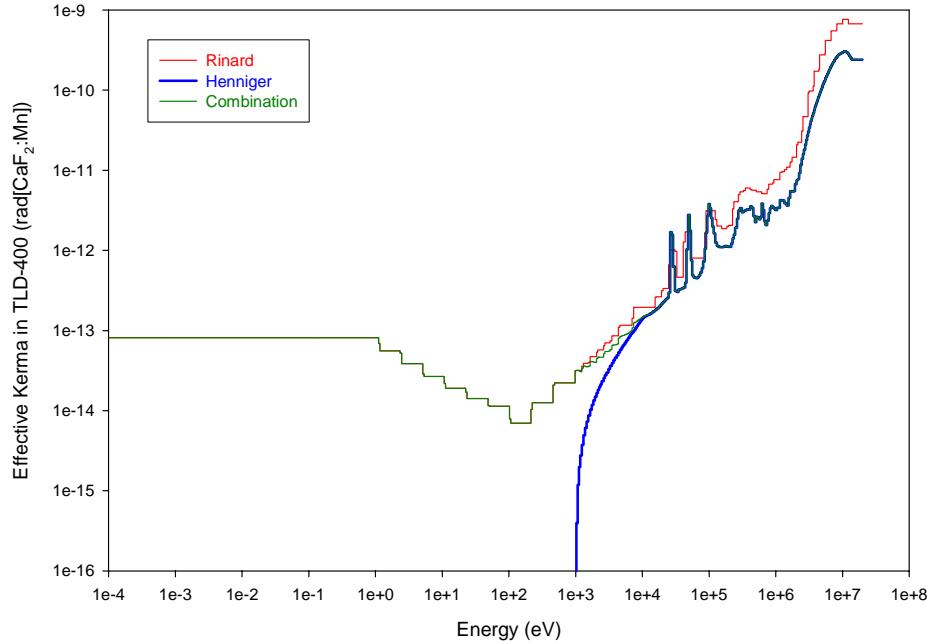


Figure 3: The Effective Neutron Kerma for  $\text{CaF}_2:\text{Mn}$  TLDs.

Table 3: Direct and Effective Neutron Kerma in TLD-400

Neutron Spectrum	Direct Neutron Kerma Rad[TLD]/(n/cm <sup>2</sup> )	Effective Neutron Kerma Rad[TLD]/(n/cm <sup>2</sup> )	TLD Efficiency %
ACF9	6.39044E-11	6.55665E-12	10.26
SPR3CC	1.23388E-10	1.33989E-11	10.86
WB7	4.22488E-11	4.50463E-12	10.66
SPR_80a3	8.04630E-11	8.77258E-12	10.90
FRECIIP6	2.51732E-11	3.22609E-12	12.82
Maxwellian Thermal	4.25488E-13	8.07201E-14	18.97

Table 3 demonstrates that the neutron induced charged particles are much less efficient at populating the thermoluminescent traps. For the measured reactor spectra, the efficiency of converting neutron induced ionization into TLD response is between 10-13%. As the neutron spectrum becomes more thermal, the efficiency of this process increases to about 19%.

### 3.2 Secondary $\gamma$ Dose

Secondary  $\gamma$ 's produced in the aluminum equilibrator and the TLD-400 material are another contributor to the overall neutron response of  $\text{CaF}_2:\text{Mn}$  TLDs. These  $\gamma$ 's are produced by neutron capture and inelastic scattering events in the equilibrated TLD. It is generally believed that the photons that are created in the equilibrated TLD do not deposit a large amount of energy

in the TLD crystal. However, the TLD does respond to the secondary  $\gamma$  ionization with the same efficiency as it does to direct  $\gamma$  radiation. To determine the contribution of secondary  $\gamma$ 's to the total TLD response, the secondary  $\gamma$  dose in the TLD was determined during the same calculations for the neutron kerma and effective neutron kerma. The results of these calculations are displayed in Table 4. Note that the secondary  $\gamma$  dose is directly related to both the neutron fluence and energy spectrum of the neutrons. This is demonstrated by the increased dose in the extremely moderated WB7, FRECIIp6, and Maxwellian thermal spectra and the decreased dose for the hard SPR3CC spectrum.

Table 4: Secondary  $\gamma$  Dose in  $\text{CaF}_2:\text{Mn}$  TLDs

Neutron Spectrum	Secondary $\gamma$ Dose Rad[TLD]/(n/cm <sup>2</sup> )
ACF9	2.81646E-12
SPR3CC	2.76820E-12
WB7	5.69136E-12
SPR_80a3	2.81248E-12
FRECIIp6	1.08586E-11
Maxwellian Thermal	2.63548E-11

### 3.3 Dose from TLD Activation Products

The neutron interactions within the TLD produce radioactive atoms in the crystal itself. In most cases,  $\beta$ -decay is the most prominent decay mode for these radioactive atoms. Since direct  $\gamma$  interactions produce ionizations (electrons) that are converted to TLD response (light output), it is assumed that the  $\beta$ 's create ionizations and TLD response in an identical manner. A radioactive atom that undergoes transformation by  $\beta$ -decay deposits energy in the surrounding matter by three main mechanisms. The first mechanism is the ionization created by the  $\beta$ -particle in the material. The second mechanism is the energy deposited by the decay  $\gamma$ 's that result from the decay process leaving the residual nucleus in an excited state. The third mechanism is the energy deposited by the internal bremsstrahlung (IB) or x-ray production that accompanies  $\beta$ -decay. Using the  $\beta$ -decay of  $^{19}\text{O}$ , Figure 4 shows the mechanisms that are described above for the energy released during a  $\beta$ -decay. In Figure 4,  $\langle\beta\rangle$  represents the average energy of the  $\beta$ -decay spectrum,  $\langle\text{IB}\rangle$  represents the average energy of the internal bremsstrahlung continuum, and  $\langle\gamma\rangle$  represents the average of the resulting discrete  $\gamma$ -rays in the decay process.

The ANITA [Po92] code was used to calculate the time-dependent activation products in  $\text{CaF}_2:\text{Mn}$  TLDs for an exposure to a neutron flux of  $10^{14}$  n/cm<sup>2</sup>-s for  $10^4$  seconds for each of the six neutron spectra. The ANITA output was examined for the isotopes that could make the largest contributions to the activation dose based on the number of atoms/cm<sup>3</sup> created and the half-life of the isotope. Four isotopes were identified as the largest contributors based on these criteria:  $^{16}\text{N}$ ,  $^{19}\text{O}$ ,  $^{20}\text{F}$ , and  $^{56}\text{Mn}$ .

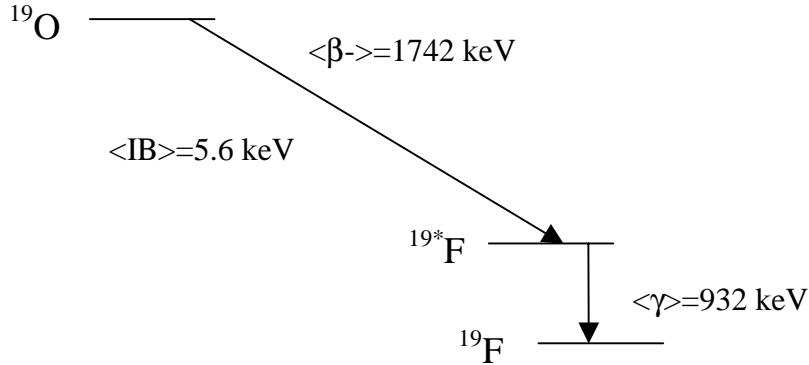


Figure 4: Schematic of  $^{19}\text{O}$   $\beta$ -decay process.

The first three isotopes ( $^{16}\text{N}$ ,  $^{19}\text{O}$ , and  $^{20}\text{F}$ ) are short-lived with the longest half-life being 27.08 seconds. These isotopes deposit all their energy within the TLD within the first hour after irradiation. The fourth isotope ( $^{56}\text{Mn}$ ) has a half-life of 2.578 hours, so the majority of its dose is delivered in the first day. Using Reference [Br86] for the energy spectra of the  $\beta$ 's, the energy spectra of the decay  $\gamma$ 's, and the energy spectra of the internal bremsstrahlung photons, four separate calculations were performed to determine the average energy deposition per decay for each isotope. The first calculation involved  $\beta$ 's less than 100 keV and assumed all the energy of these  $\beta$ -particles was deposited in the TLD. The 100 keV cutoff was selected because the range of an electron below 100 keV is less than the average dimension of the TLD-400 chip. Using the  $\beta$ -spectrum (above 100 keV) from Reference [Br86], a uniform source of  $\beta$ 's for each isotope was placed into MCNP and the average energy deposited in the TLD per decay was calculated. The results of these two calculations were added together to get a total energy deposited by  $\beta$ -particles per decay. Next, a similar calculation was performed for the  $\gamma$ -rays that result from  $\beta$ -decay process. Finally, a calculation was performed for the internal bremsstrahlung photons that are produced as a result of  $\beta$ -decay. Thus, for each process from the decay of the activation products that can deposit energy, an average energy deposited in the TLD per decay was calculated and multiplied by the total number of decays that resulted from the reference irradiation. The results of these calculations were summed and are displayed for the three environments and at three different times (1 hour, 1 day, and 1 week) in Table 5. The  $\beta$ -decay process accounts for ~97% of the energy deposited by the activation products while the  $\gamma$ -rays represents ~3%. The energy deposited by IB represents for less than 0.04% of the total energy deposited by the activation products.

Table 5: Activation Product Dose From  $\text{CaF}_2:\text{Mn}$  TLDs

Neutron Spectrum	TLD Activation Dose @ 1 hour Rad[TLD]/(n/cm <sup>2</sup> )	TLD Activation Dose @ 1 day Rad[TLD]/(n/cm <sup>2</sup> )	TLD Activation Dose @ 1 week Rad[TLD]/(n/cm <sup>2</sup> )
ACF9	7.31290E-13	1.72842E-12	1.73048E-12
SPR3CC	5.92967E-13	6.00371E-13	6.00386E-13
WB7	1.35916E-12	4.14268E-12	4.14843E-12
SPR_80a3	1.09646E-12	1.28117E-12	1.28241E-12
FRECIIP6	6.40887E-12	8.33465E-12	8.34672E-12
Maxwellian Thermal	4.14874E-12	1.47545E-11	1.47764E-11

### **3.4 Dose From Aluminum Activation Products**

In addition to producing activation products in the TLD, the neutrons activate atoms in the aluminum equilibrator. For the activation products in the aluminum, a calculation very similar to that for activation in the TLD was performed. An ANITA calculation was used to determine the time-dependent activation products in  $\text{CaF}_2:\text{Mn}$  TLDs for an exposure to a neutron flux of  $10^{14} \text{n/cm}^2\text{-s}$  for  $10^{-4}$  seconds for each of the six neutron spectra. The ANITA output was examined for the isotopes that could make the largest contributions to the activation dose based on the number of atoms/ $\text{cm}^3$  created and the half-life of the isotope. There were twelve isotopes ( $^{24}\text{Na}$ ,  $^{25}\text{Na}$ ,  $^{27}\text{Mg}$ ,  $^{28}\text{Al}$ ,  $^{31}\text{Si}$ ,  $^{47}\text{Sc}$ ,  $^{51}\text{Ti}$ ,  $^{52}\text{V}$ ,  $^{55}\text{Cr}$ ,  $^{56}\text{Mn}$ ,  $^{64}\text{Cu}$ , and  $^{66}\text{Cu}$ ) identified in the ANITA output as being major contributors to the activation dose from the aluminum equilibrator.

For each of the twelve isotopes, a  $\beta$ -source uniformly distributed throughout the aluminum equilibrator with the energy spectrum from Reference [Br86] was used to calculate the energy deposited in the TLD by the  $\beta$ -particles. A similar calculation was performed for the  $\gamma$ -rays that result from the  $\beta$ -decay process. A calculation of the energy deposited by the internal bremsstrahlung from each  $\beta$ -decay was also performed. The results of these three calculations were combined. Thus, for each process from the decay of the activation products that can deposit energy, an average energy deposited in the TLD per decay was calculated and multiplied by the total number of decays that resulted from the reference irradiation. The results of these calculations were summed and are displayed for the six environments and at three different times (1 hour, 1 day, and 1 week) in Table 6. Note that the dose from the activation of the aluminum equilibrator is larger than the contribution of the neutron kerma for all the spectra except those from the SPR-III reactor. This is most likely due to the fact that the SPR-III spectra have a higher average neutron energy and will not produce as much activation in the aluminum equilibrator as the ACRR reactor spectra. Also, note that majority of the activation dose is deposited within the first hour after the irradiation.

Table 6: Activation Product Dose From Aluminum Equilibrator

Neutron Spectrum	Al Activation Dose @ 1 hour Rad[TLD]/(n/cm <sup>2</sup> )	Al Activation Dose @ 1 day Rad[TLD]/(n/cm <sup>2</sup> )	Al Activation Dose @ 1 week Rad[TLD]/(n/cm <sup>2</sup> )
ACF9	1.40709E-11	1.44483E-11	1.44638E-11
SPR3CC	1.26622E-12	1.33120E-12	1.35931E-12
WB7	4.07741E-11	4.17681E-11	4.17845E-11
SPR_80a3	8.50201E-12	8.75160E-12	8.77071E-12
FRECIIp6	8.97118E-11	9.17657E-11	9.17868E-11
Maxwellian Thermal	1.65714E-10	1.65803E-10	1.65821E-10

### **3.5 Dose From Charged Particles Produced By High Energy Neutrons**

The dose contribution of the charged particles produced in the aluminum equilibrator was calculated by using bounding approximations. First, since the aluminum equilibrator is made up of 96.68% aluminum (by mass), it is assumed that all of the charged particles are produced by reactions in  $^{27}\text{Al}$ . Next, an energy of 8 MeV was assumed to be the highest energy neutron in the

three spectra. This approximation was determined to account for more 99.75% of the total neutrons in the spectra. Next, Q-values of -2 MeV and -3 MeV were assumed for the  $^{27}\text{Al}(\text{n}, \text{p})$  and  $^{27}\text{Al}(\text{n}, \alpha)$  reactions respectively. Thus, the highest energy protons produced would be 6 MeV, and the highest energy  $\alpha$ -particles produced would be 5 MeV. These energies were used to determine a range of the charged produced from Reference [ICRU]. The range for a 6 MeV proton was determined to be 0.026096 cm while a 5 MeV  $\alpha$ -particle has a range of  $2.14945 \times 10^{-3}$  cm. The ranges were then used to determine the total volume of the equilibrator that can produce charged particles that deposit energy in the TLD.

The resulting volume of the aluminum equilibrator was divided into 6 regions based on a continuous slowing down approximation for the protons. The protons from the region farthest from the TLD were assumed to deposit 1 MeV in the TLD while those from the region closest to the TLD were assumed to deposit 6 MeV (highest energy possible for the particle) in the TLD. The regions between the extremes were assumed to deposit 2, 3, 4, and 5 MeV respectively. The results of these bounding calculations are shown in Table 7.

Table 7: Charged Particle Dose from Aluminum Equilibrator

<b>Neutron Spectrum</b>	<b>Proton Dose Rad[TLD]/(n/cm<sup>2</sup>)</b>	<b><math>\alpha</math>-Particle Dose Rad[TLD]/(n/cm<sup>2</sup>)</b>	<b>Total Dose Rad[TLD]/(n/cm<sup>2</sup>)</b>
ACF9	5.93245E-13	1.01427E-14	6.03387E-13
SPR3CC	1.28723E-12	7.83688E-14	1.36559E-12
WB7	5.18298E-13	8.54679E-15	5.26845E-13
SPR_80a3	1.55563E-12	1.32578E-14	1.56889E-12
FRECIIP6	8.64939E-13	8.18835E-15	8.73128E-13
Maxwellian Thermal	0.00000E+00	0.00000E+00	0.00000E+00

The volume of aluminum that was determined by the  $\alpha$ -particle range was determined to produce less than  $490 \alpha$ -particles/( $10^{10}$  n/cm<sup>2</sup>) for all six neutron spectra and only half of these are assumed to deposit energy in the TLD. Since there are so few produced, all the  $\alpha$ -particles that deposit energy are assumed to deposit 5 MeV (highest energy possible for the particle) in the TLD. The results of these bounding calculations are found in Table 7. Note that the doses contributed by  $\alpha$ -particles are about an order of magnitude lower than those contributed by protons. Also, note that the total contribution to the TLD dose by the charged particles is the smallest of the five contributions that were considered for all of the neutron spectra except those from the SPR-III reactor.

## 4. SUMMARY

Table 8 summarizes all of the various components that were considered in the above analysis. The results in Table 8 also show the time dependence of the neutron contribution with time points at 1 hour, 1 day, and 1 week. The results displayed in Table 8 were used to perform an analysis on the dosimetry shots that were used to produce the reactor spectra. The post-experiment analysis of the dosimetry shots used either the neutron fluence given in Reference [Gr94] or was calculated from information given in Reference [Gr94]. The analysis assumed that the TLD-400 chips were read 1 day after the irradiation. The results of these post-experiment analyses are found in Tables 9-13. Note that the largest contribution (~13%) from neutrons was

the FRECIIp6 spectrum. Of the experimental spectra that were studied, the FRECIIp6 spectrum was the most moderated. The uncertainty in a TLD reading is typically 4-12% (based on the statistics of the reading), so the neutron contribution to the TLD response is within that uncertainty for all but the FRECIIp6 spectrum.

Table 8: Summary Table for Neutron Contributions to CaF<sub>2</sub>:Mn TLD Dose

EFFECT	ACF9	SPR3CC	WB7	SPR_80a3	FRECIIp6	Maxwellian Thermal
<b>Direct <sup>1</sup>n:</b>						
Kerma	6.39044E-11	1.23388E-10	4.22488E-11	8.04630E-11	2.51732E-11	4.25488E-13
Effective Kerma	6.55665E-12	1.33989E-11	4.50463E-12	8.77258E-12	3.22609E-12	8.07201E-14
Secondary $\gamma$	2.81646E-12	2.76820E-12	5.69136E-12	2.81248E-12	1.08586E-11	2.63548E-11
<b>TLD Activation</b>						
1 hour	7.31290E-13	5.92967E-13	1.35916E-12	1.09646E-12	6.40887E-12	4.14874E-12
1 day	1.72842E-12	6.00371E-13	4.14268E-12	1.28117E-12	8.33465E-12	1.47545E-11
1 week	1.73048E-12	6.00386E-13	4.14843E-12	1.28241E-12	8.34672E-12	1.47764E-11
<b>Aluminum Activation</b>						
1 hour	1.40709E-11	1.26622E-12	4.07741E-11	8.50201E-12	8.97118E-11	1.65714E-10
1 day	1.44483E-11	1.33120E-12	4.17681E-11	8.75160E-12	9.17657E-11	1.65803E-10
1 week	1.44638E-11	1.35931E-12	4.17845E-11	8.77071E-12	9.17868E-11	1.65821E-10
<b>Charged Particles</b>						
Protons	5.93245E-13	1.28723E-12	5.18298E-13	1.55563E-12	8.64939E-13	0.00000E+00
$\alpha$ -Particles	1.01427E-14	7.83688E-14	8.54679E-15	1.32578E-14	8.18835E-15	0.00000E+00
Total Charged Particle	6.03387E-13	1.36559E-12	5.26845E-13	1.56889E-12	8.73128E-13	0.00000E+00
<b>TOTAL for 1 hour</b>	<b>2.47787E-11</b>	<b>1.93919E-11</b>	<b>5.28561E-11</b>	<b>2.27524E-11</b>	<b>1.11078E-10</b>	<b>1.96298E-10</b>
<b>TOTAL for 1 day</b>	<b>2.61532E-11</b>	<b>1.94643E-11</b>	<b>5.66336E-11</b>	<b>2.31867E-11</b>	<b>1.15058E-10</b>	<b>2.06993E-10</b>
<b>TOTAL for 1 week</b>	<b>2.61708E-11</b>	<b>1.94924E-11</b>	<b>5.66557E-11</b>	<b>2.32071E-11</b>	<b>1.15091E-10</b>	<b>2.07033E-10</b>

For ACF9 Dosimetry Shot (See Reference [Gr94]):

- Neutron Fluence: 3.505201E+14 (n/cm<sup>2</sup>)
- CaF<sub>2</sub>:Mn Dose: 1.97800E+05 {Rad[TLD]}
- Assume time is 1 day between irradiation and TLD Reading.

Table 9: Summary of ACF9 Dosimetry Shot

<b>Effect</b>	<b>Dose (Rad[TLD])</b>	<b>Contribution (%)</b>
Measured TLD	1.97800E+05	100
Neutron Dose	2.29824E+03	1.16
Secondary $\gamma$ Dose	9.87226E+02	0.50
TLD Activation	6.05846E+02	0.31
Aluminum Activation	5.06442E+03	2.56
Charged Particle Dose	2.11499E+02	0.11
<b>TOTAL</b>	<b>9.16723E+03</b>	<b>4.64</b>

For SPR3CC Dosimetry Shot (See Reference [Gr94]):

- Neutron Fluence: 1.369764E+13 (n/cm<sup>2</sup>)
- CaF<sub>2</sub>:Mn Dose: 3.91700E+03 {Rad[TLD]}
- Assume time is 1 day between irradiation and TLD Reading.

Table 10: Summary of SPR3CC Dosimetry Shot

<b>Effect</b>	<b>Dose (Rad[TLD])</b>	<b>Contribution (%)</b>
Measured TLD	3.91700E+03	100
Neutron Dose	1.83533E+02	4.69
Secondary $\gamma$ Dose	3.79177E+01	0.97
TLD Activation	8.22365E+00	0.21
Aluminum Activation	1.82343E+01	0.46
Charged Particle Dose	1.87053E+01	0.48
<b>TOTAL</b>	<b>2.66614E+02</b>	<b>6.81</b>

For WB7 Dosimetry Shot (See Reference [Gr94]):

- Neutron Fluence:  $6.552314\text{E+14}$  ( $\text{n/cm}^2$ ) – Calculated from  $\Phi_{3\text{MeV}}^{*}$
- CaF<sub>2</sub>:Mn Dose:  $5.37800\text{E+05}$  {Rad[TLD]}
- Assume time is 1 day between irradiation and TLD Reading.

\* $\Phi_{3\text{MeV}}$  is the number of neutrons ( $\text{n/cm}^2$ ) that have energy greater than 3 MeV.

Table 11: Summary of WB7 Dosimetry Shot

<b>Effect</b>	<b>Dose (Rad[TLD])</b>	<b>Contribution (%)</b>
Measured TLD	$5.37800\text{E+05}$	100
Neutron Dose	$2.95158\text{E+03}$	0.55
Secondary $\gamma$ Dose	$3.72916\text{E+03}$	0.69
TLD Activation	$2.71441\text{E+03}$	0.50
Aluminum Activation	$2.73678\text{E+04}$	5.09
Charged Particle Dose	$3.45205\text{E+02}$	0.06
<b>TOTAL</b>	<b><math>3.71081\text{E+04}</math></b>	<b>6.90</b>

For SPR\_80a3 Dosimetry Shot (See Reference [Gr94]):

- Neutron Fluence:  $1.043041\text{E+13}$  ( $\text{n/cm}^2$ ) – Calculated from  $\Phi_{3\text{MeV}}$
- CaF<sub>2</sub>:Mn Dose:  $2.21700\text{E+03}$  Rad[TLD]}
- Assume time is 1 day between irradiation and TLD Reading.

Table 12: Summary of SPR\_80a3 Dosimetry Shot

<b>Effect</b>	<b>Dose (Rad[TLD])</b>	<b>Contribution (%)</b>
Measured TLD	$2.21700\text{E+03}$	100
Neutron Dose	$9.15016\text{E+01}$	4.13
Secondary $\gamma$ Dose	$2.93353\text{E+01}$	1.32
TLD Activation	$1.33631\text{E+01}$	0.60
Aluminum Activation	$9.12828\text{E+01}$	4.12
Charged Particle Dose	$1.63642\text{E+01}$	0.74
<b>TOTAL</b>	<b><math>2.41847\text{E+02}</math></b>	<b>10.91</b>

For FRECIIp6 Dosimetry Shot (See Reference [Gr94]):

- Neutron Fluence:  $1.214156\text{E+14}$  ( $\text{n/cm}^2$ ) – Calculated from  $\Phi_{3\text{MeV}}$
- $\text{CaF}_2:\text{Mn}$  Dose:  $1.00500\text{E+05}$  {Rad[TLD]}
- Assume time is 1 day between irradiation and TLD Reading.

Table 13: Summary of FRECIIp6 Dosimetry Shot

<b>Effect</b>	<b>Dose (Rad[TLD])</b>	<b>Contribution (%)</b>
Measured TLD	$1.00500\text{E+05}$	100
Neutron Dose	$3.91698\text{E+02}$	0.39
Secondary $\gamma$ Dose	$1.31840\text{E+03}$	1.31
TLD Activation	$1.01196\text{E+03}$	1.01
Aluminum Activation	$1.11418\text{E+04}$	11.09
Charged Particle Dose	$1.06011\text{E+02}$	0.11
<b>TOTAL</b>	<b><math>1.39699\text{E+04}</math></b>	<b>13.90</b>

## 5. CONCLUSIONS

The neutron component of the response of TLD-400 ( $\text{CaF}_2:\text{Mn}$ ) chips has been quantified for five measured reactor spectra and one theoretical neutron spectrum. Activation of the aluminum equilibrator is the main source of the neutron response in the TLD-400 chips for all the reactor environments except the SPR3CC spectrum which has the highest average neutron energy. The neutron response was less than 14% of the total TLD response for all five reactor environments investigated (less than 7% for three of the five spectra). Users of SNL reactor facilities require a quantification of the uncertainty for the dosimetry results that are reported to them. The calculations produced for this report will aid the SNL-RML in the quantification and interpretation of the uncertainty for TLD photon dosimetry measurements in the mixed field environments produced by SNL reactor facilities.

## 6. REFERENCES

- [Gr94] P. J. Griffin, J. G. Kelly, D. W. Vehar, **Updated Neutron Spectrum Characterization of SNL Baseline Reactor Environments, Vol. 1: Characterization**, Sandia National Laboratories, Albuquerque, NM, report SAND93-2554, April 1994.
- [Br00] J. F. Briesmeister (Editor), *MCNP-A General Monte Carlo N-Particle Transport Code, Version 4C*, LA-13709-M, Los Alamos National Laboratory, Los Alamos, NM, April 2000.
- [He82] J. Henninger, H. Hubner, G. Pretzsch, **Calculation of the Neutron Sensitivity of TL Detectors**, Nuclear Instruments and Methods, Vol. 192, pp. 453-461, 1982.
- [Ri79] P. Rinard, G. Simons, **Calculated Neutron Sensitivities of CaF<sub>2</sub> and <sup>7</sup>LiF Thermoluminescent Dosimeters**, Nuclear Instruments and Methods, Vol. 158, pp. 545-549, 1979.
- [Po92] C. Ponti, S. Stramaccia, *ANITA: Analysis of Neutron Induced Transmutation and Activation*, EUR 12622 EN, Commission of the European Communities Joint Research Center, Ispra, Italy, September 1992.
- [Br86] E. Browne, R. B. Firestone, V. S. Shirley (Editor), *Table of Radioactive Isotopes*, John Wiley and Sons, New York, 1986.
- [ICRU] International Commission on Radiation Units and Measurements, *ICRU Report 49: Stopping Powers and Ranges for Protons and Alpha Particles*, Bethesda, MD, May 1993.

## APPENDIX A – MCNP4C3 Sample Input Deck for Neutron Kerma and Secondary $\gamma$ Kerma – ACF9 Neutron Spectrum

```

Model of TLD-400 with Al Equilibrator with ACF9 Spectrum from PJG
C **** CELL CARDS ****
C *   CELL CARDS *
C **** -----
C C | Mat | Density | X-plane | Y-plane | Z-plane | Import- | Comment
C # | #  |        | L      | R      | L      | R      | B      | T      | ance
C -----+-----+-----+-----+-----+-----+-----+
 100    1    -3.1000   -100          IMP:N=1 IMP:P=1 $TLD-400
 200    2    -2.7100    100    -200          IMP:N=1 IMP:P=1 $Al equil.
 300    0     200   -300          IMP:N=1 IMP:P=1 $Void
 301    0     300          IMP:N=0 IMP:P=0 $Void

C **** SURFACE CARDS ****
C *   SURFACE CARDS *
C **** -----
C Srf|Sym-| Dim-1 | Dim-2 | Dim-3 | Comment
C # | bol |        |        |        |
C -----+-----+-----+-----+-----+
 100  rpp  -0.15000  0.15000  -0.15000  0.15000
           -0.04445  0.04445          $TLD-400          (0.3x0.3x0.0889 cm)
 200  rpp  -0.40000  0.40000  -0.40000  0.40000
           -0.27305  0.27305          $Al equilibrator (0.8x0.8x0.5461 cm)
 300  so   2.00000          $Source sphere

C **** DATA CARDS ****
C *   DATA CARDS *
C **** -----
MODE N P          $Neutron and Secondary Gammas
PHYS:P  100.0
C **** -----
C *   SOURCE CARDS *
C **** -----
SDEF SUR=300 NRM=-1 DIR=D1 WGT=12.56637061 ERG=D2
C WGT=PI*(radius of sphere)^2
C Weighted to give 1 n/cm^2/src-n
SB1  -21 2
C 641 Group energy grid from PJG ACF9
SI2  H 1.00000E-10 1.05000E-10 1.10000E-10 1.15000E-10 1.20000E-10
     1.27500E-10 1.35000E-10 1.42500E-10 1.50000E-10 1.60000E-10
     1.70000E-10 1.80000E-10 1.90000E-10 2.00000E-10 2.10000E-10
     2.20000E-10 2.30000E-10 2.40000E-10 2.55000E-10 2.70000E-10
     2.80000E-10 3.00000E-10 3.20000E-10 3.40000E-10 3.60000E-10
     3.80000E-10 4.00000E-10 4.25000E-10 4.50000E-10 4.75000E-10
     5.00000E-10 5.25000E-10 5.50000E-10 5.75000E-10 6.00000E-10
     6.30000E-10 6.60000E-10 6.90000E-10 7.20000E-10 7.60000E-10
     8.00000E-10 8.40000E-10 8.80000E-10 9.20000E-10 9.60000E-10
     1.00000E-09 1.05000E-09 1.10000E-09 1.15000E-09 1.20000E-09
     1.27500E-09 1.35000E-09 1.42500E-09 1.50000E-09 1.60000E-09
     1.70000E-09 1.80000E-09 1.90000E-09 2.00000E-09 2.10000E-09
     2.20000E-09 2.30000E-09 2.40000E-09 2.55000E-09 2.70000E-09
     2.80000E-09 3.00000E-09 3.20000E-09 3.40000E-09 3.60000E-09
     3.80000E-09 4.00000E-09 4.25000E-09 4.50000E-09 4.75000E-09
     5.00000E-09 5.25000E-09 5.50000E-09 5.75000E-09 6.00000E-09
     6.30000E-09 6.60000E-09 6.90000E-09 7.20000E-09 7.60000E-09
     8.00000E-09 8.40000E-09 8.80000E-09 9.20000E-09 9.60000E-09
     1.00000E-08 1.05000E-08 1.10000E-08 1.15000E-08 1.20000E-08
     1.27500E-08 1.35000E-08 1.42500E-08 1.50000E-08 1.60000E-08
     1.70000E-08 1.80000E-08 1.90000E-08 2.00000E-08 2.10000E-08
     2.20000E-08 2.30000E-08 2.40000E-08 2.55000E-08 2.70000E-08
     2.80000E-08 3.00000E-08 3.20000E-08 3.40000E-08 3.60000E-08
     3.80000E-08 4.00000E-08 4.25000E-08 4.50000E-08 4.75000E-08
     5.00000E-08 5.25000E-08 5.50000E-08 5.75000E-08 6.00000E-08
     6.30000E-08 6.60000E-08 6.90000E-08 7.20000E-08 7.60000E-08
     8.00000E-08 8.40000E-08 8.80000E-08 9.20000E-08 9.60000E-08
     1.00000E-07 1.05000E-07 1.10000E-07 1.15000E-07 1.20000E-07
     1.27500E-07 1.35000E-07 1.42500E-07 1.50000E-07 1.60000E-07
     1.70000E-07 1.80000E-07 1.90000E-07 2.00000E-07 2.10000E-07
     2.20000E-07 2.30000E-07 2.40000E-07 2.55000E-07 2.70000E-07
     2.80000E-07 3.00000E-07 3.20000E-07 3.40000E-07 3.60000E-07
     3.80000E-07 4.00000E-07 4.25000E-07 4.50000E-07 4.75000E-07

```



1.15000E+01	1.16000E+01	1.17000E+01	1.18000E+01	1.19000E+01
1.20000E+01	1.21000E+01	1.22000E+01	1.23000E+01	1.24000E+01
1.25000E+01	1.26000E+01	1.27000E+01	1.28000E+01	1.29000E+01
1.30000E+01	1.31000E+01	1.32000E+01	1.33000E+01	1.34000E+01
1.35000E+01	1.36000E+01	1.37000E+01	1.38000E+01	1.39000E+01
1.40000E+01	1.41000E+01	1.42000E+01	1.43000E+01	1.44000E+01
1.45000E+01	1.46000E+01	1.47000E+01	1.48000E+01	1.49000E+01
1.50000E+01	1.51000E+01	1.52000E+01	1.53000E+01	1.54000E+01
1.55000E+01	1.56000E+01	1.57000E+01	1.58000E+01	1.59000E+01
1.60000E+01	1.61000E+01	1.62000E+01	1.63000E+01	1.64000E+01
1.65000E+01	1.66000E+01	1.67000E+01	1.68000E+01	1.69000E+01
1.70000E+01	1.71000E+01	1.72000E+01	1.73000E+01	1.74000E+01
1.75000E+01	1.76000E+01	1.77000E+01	1.78000E+01	1.79000E+01
1.80000E+01	1.81000E+01	1.82000E+01	1.83000E+01	1.84000E+01
1.85000E+01	1.86000E+01	1.87000E+01	1.88000E+01	1.89000E+01
1.90000E+01	1.91000E+01	1.92000E+01	1.93000E+01	1.94000E+01
1.95000E+01	1.96000E+01	1.97000E+01	1.98000E+01	1.99000E+01
2.00000E+01				

C

SP2	D	0.00000E+00	4.22801E-08	4.43342E-08	4.63883E-08	4.84423E-08
		7.65150E-08	8.11153E-08	8.57370E-08	9.03374E-08	1.27611E-07
		1.35798E-07	1.43958E-07	1.52117E-07	1.60276E-07	1.68436E-07
		1.76595E-07	1.84726E-07	1.92856E-07	3.04520E-07	3.22792E-07
		2.25323E-07	4.74952E-07	5.07304E-07	5.39599E-07	5.71723E-07
		6.04246E-07	6.36199E-07	8.40182E-07	8.90821E-07	9.40746E-07
		9.89959E-07	1.03989E-06	1.08981E-06	1.13902E-06	1.18895E-06
		1.49179E-06	1.56282E-06	1.63301E-06	1.70404E-06	2.38161E-06
		2.50600E-06	2.63038E-06	2.75477E-06	2.87801E-06	3.00126E-06
		3.12336E-06	4.07681E-06	4.26652E-06	4.45624E-06	4.64596E-06
		7.31985E-06	7.74137E-06	8.15860E-06	8.57584E-06	1.20764E-05
		1.28039E-05	1.35256E-05	1.42417E-05	1.49521E-05	1.56568E-05
		1.63557E-05	1.70490E-05	1.77365E-05	2.78801E-05	2.93949E-05
		2.04297E-05	4.28336E-05	4.54240E-05	4.79745E-05	5.04794E-05
		5.29442E-05	5.53693E-05	7.25352E-05	7.61727E-05	7.97388E-05
		8.32336E-05	8.66571E-05	8.99379E-05	9.32188E-05	9.64283E-05
		1.19822E-04	1.24187E-04	1.28381E-04	1.32489E-04	1.82928E-04
		1.89776E-04	1.96394E-04	2.02671E-04	2.08833E-04	2.14653E-04
		2.20245E-04	2.82866E-04	2.90854E-04	2.98414E-04	3.05547E-04
		4.70944E-04	4.84852E-04	4.97476E-04	5.09030E-04	6.94683E-04
		7.10945E-04	7.24639E-04	7.36336E-04	7.46036E-04	7.53738E-04
		7.60015E-04	7.64294E-04	7.67432E-04	1.15329E-03	1.15286E-03
		7.66291E-04	1.52231E-03	1.50348E-03	1.47895E-03	1.44928E-03
		1.41504E-03	1.37796E-03	1.66681E-03	1.60119E-03	1.53344E-03
		1.46426E-03	1.39721E-03	1.33659E-03	1.28096E-03	1.23032E-03
		1.41476E-03	1.35513E-03	1.29665E-03	1.24273E-03	1.57595E-03
		1.49036E-03	1.41276E-03	1.34315E-03	1.28039E-03	1.22219E-03
		1.16969E-03	1.39564E-03	1.32960E-03	1.26969E-03	1.21477E-03
		1.72886E-03	1.62851E-03	1.53907E-03	1.45884E-03	1.83385E-03
		1.72088E-03	1.62131E-03	1.53201E-03	1.45213E-03	1.38280E-03
		1.32204E-03	1.26612E-03	1.21477E-03	1.73400E-03	1.63557E-03
		1.03903E-03	1.96794E-03	1.83784E-03	1.72259E-03	1.62102E-03
		1.53087E-03	1.45156E-03	1.71460E-03	1.61546E-03	1.52773E-03
		1.44928E-03	1.38081E-03	1.32161E-03	1.26741E-03	1.21748E-03
		1.40021E-03	1.34030E-03	1.28466E-03	1.23417E-03	1.57138E-03
		1.49493E-03	1.42531E-03	1.36255E-03	1.30435E-03	1.25186E-03
		1.20279E-03	1.44072E-03	1.37810E-03	1.32047E-03	1.26769E-03
		1.81124E-03	1.71389E-03	1.62659E-03	1.54806E-03	1.95510E-03
		1.84355E-03	1.74455E-03	1.65583E-03	1.57595E-03	1.49978E-03
		1.42674E-03	1.36055E-03	1.30007E-03	1.84783E-03	1.73742E-03
		1.10350E-03	2.08947E-03	1.95595E-03	1.84469E-03	1.74712E-03
		1.66325E-03	1.59306E-03	1.91644E-03	1.84512E-03	1.75097E-03
		1.66467E-03	1.58265E-03	1.50277E-03	1.41290E-03	1.32090E-03
		1.49350E-03	1.41048E-03	1.33773E-03	1.27439E-03	1.61361E-03
		1.52574E-03	1.44814E-03	1.37738E-03	1.31348E-03	1.25528E-03
		1.20164E-03	1.42931E-03	1.35199E-03	1.28210E-03	1.21848E-03
		1.72094E-03	1.60690E-03	1.50591E-03	1.41625E-03	1.76481E-03
		1.64071E-03	1.53173E-03	1.43558E-03	1.35000E-03	1.26983E-03
		1.19451E-03	1.12661E-03	1.06528E-03	1.49564E-03	1.38651E-03
		8.70423E-04	1.62673E-03	1.50634E-03	1.41447E-03	1.33345E-03
		1.26041E-03	1.19537E-03	1.41219E-03	1.33088E-03	1.25885E-03
		1.19394E-03	1.13332E-03	1.08482E-03	1.06057E-03	1.01207E-03
		1.15543E-03	1.09723E-03	1.03989E-03	9.60289E-04	1.20050E-03
		1.11697E-03	1.04314E-03	9.77521E-04	9.11447E-04	8.58954E-04
		8.13877E-04	9.68277E-04	9.28907E-04	8.93246E-04	8.60294E-04
		1.23331E-03	1.17169E-03	1.11649E-03	1.06663E-03	1.35199E-03
		1.27953E-03	1.21448E-03	1.15058E-03	1.08781E-03	1.03675E-03
		9.88818E-04	9.44884E-04	9.05797E-04	1.28894E-03	1.21149E-03
		7.60301E-04	1.42703E-03	1.33801E-03	1.26327E-03	1.19594E-03

1.13717E-03 1.08981E-03 1.32946E-03 1.29237E-03 1.24815E-03  
 1.20678E-03 1.19679E-03 1.22319E-03 1.17897E-03 1.13831E-03  
 1.31719E-03 1.26755E-03 1.16912E-03 1.12462E-03 1.41504E-03  
 1.34771E-03 1.28609E-03 1.23246E-03 1.19594E-03 1.13238E-03  
 1.02842E-03 1.21862E-03 1.16641E-03 1.10878E-03 1.06756E-03  
 1.55812E-03 1.54549E-03 1.47124E-03 1.40042E-03 1.76909E-03  
 1.66581E-03 1.58935E-03 1.55370E-03 1.47353E-03 1.40277E-03  
 1.34315E-03 1.27411E-03 1.22590E-03 1.75154E-03 1.66296E-03  
 1.07184E-03 2.07464E-03 1.95196E-03 1.88121E-03 1.84925E-03  
 1.81959E-03 1.79448E-03 2.16750E-03 2.09403E-03 2.02057E-03  
 1.96423E-03 1.87793E-03 1.80946E-03 1.73742E-03 1.66467E-03  
 1.89747E-03 1.80846E-03 1.71859E-03 1.66296E-03 2.14881E-03  
 2.06665E-03 1.99589E-03 1.92971E-03 1.87151E-03 1.81217E-03  
 1.75853E-03 2.13255E-03 2.05695E-03 1.97992E-03 1.92571E-03  
 2.79228E-03 2.67888E-03 2.58045E-03 2.49059E-03 3.16959E-03  
 3.02694E-03 2.90140E-03 2.78387E-03 2.68630E-03 2.59843E-03  
 2.51570E-03 2.43581E-03 2.36078E-03 3.40295E-03 3.25874E-03  
 2.09717E-03 4.03743E-03 3.79780E-03 3.63746E-03 3.48853E-03  
 3.35844E-03 3.23748E-03 3.94201E-03 3.78296E-03 3.62747E-03  
 3.46343E-03 3.32934E-03 3.22593E-03 3.13036E-03 3.05190E-03  
 3.58012E-03 3.48939E-03 3.39353E-03 3.29596E-03 4.23828E-03  
 4.07053E-03 3.91990E-03 3.77611E-03 3.64944E-03 3.53190E-03  
 3.42349E-03 4.14385E-03 3.97981E-03 3.85571E-03 3.74016E-03  
 5.41125E-03 5.18445E-03 5.01113E-03 4.81643E-03 6.11948E-03  
 5.79997E-03 5.52609E-03 5.28358E-03 5.07533E-03 4.89559E-03  
 4.73868E-03 4.60174E-03 4.47050E-03 6.47040E-03 6.20936E-03  
 4.00833E-03 7.73139E-03 7.35479E-03 7.00104E-03 6.68722E-03  
 6.40763E-03 6.15087E-03 7.36764E-03 7.03955E-03 6.74998E-03  
 6.47967E-03 6.22433E-03 6.01608E-03 5.82849E-03 5.65447E-03  
 6.57823E-03 6.38310E-03 6.17683E-03 5.96886E-03 7.62525E-03  
 7.29888E-03 6.99875E-03 6.71689E-03 6.46469E-03 6.26156E-03  
 6.05502E-03 1.43501E-02 1.33944E-02 1.25471E-02 1.17882E-02  
 1.11064E-02 1.04245E-02 9.71701E-03 9.10077E-03 8.56158E-03  
 8.07944E-03 7.56305E-03 7.04099E-03 6.57880E-03 6.15944E-03  
 5.78855E-03 5.45476E-03 5.15236E-03 4.87847E-03 4.62457E-03  
 4.39633E-03 4.11104E-03 3.78011E-03 3.48910E-03 3.23235E-03  
 3.00696E-03 2.80327E-03 2.62297E-03 2.45721E-03 2.30544E-03  
 2.16621E-03 1.99846E-03 1.81245E-03 1.65070E-03 1.50919E-03  
 1.38337E-03 1.27097E-03 1.17055E-03 1.07983E-03 9.97376E-04  
 9.22915E-04 8.51022E-04 7.81981E-04 7.19506E-04 6.62445E-04  
 6.11092E-04 5.64305E-04 5.21511E-04 4.82999E-04 4.48192E-04  
 4.16239E-04 3.86854E-04 3.60037E-04 3.34077E-04 3.08114E-04  
 2.84321E-04 2.62952E-04 2.43923E-04 2.27492E-04 2.13169E-04  
 1.99989E-04 1.87693E-04 1.76367E-04 1.65555E-04 1.55170E-04  
 1.45555E-04 1.36626E-04 1.28153E-04 1.20279E-04 1.13146E-04  
 1.06613E-04 9.98522E-05 9.28902E-05 8.64720E-05 8.05657E-05  
 7.51174E-05 6.99821E-05 6.51886E-05 6.07387E-05 5.65728E-05  
 5.27219E-05 4.91558E-05 4.58174E-05 4.27082E-05 3.97978E-05  
 3.70880E-05 3.45489E-05 3.21806E-05 2.99557E-05 2.78813E-05  
 2.59416E-05 2.41300E-05 2.24523E-05 2.08948E-05 1.94510E-05  
 1.81103E-05 1.68636E-05 1.57023E-05 1.46184E-05 1.36083E-05  
 1.26670E-05 1.17883E-05 1.09694E-05 1.02020E-05 9.48587E-06  
 8.81552E-06 8.19644E-06 7.62578E-06 7.10377E-06 6.61871E-06  
 6.16231E-06 5.71154E-06 5.27214E-06 4.84996E-06 4.45622E-06  
 4.09679E-06 3.77441E-06 3.48338E-06 3.21809E-06 2.97842E-06  
 2.75706E-06 2.55393E-06 2.36704E-06 2.19475E-06 2.03525E-06  
 1.88806E-06 1.75169E-06 1.62558E-06 1.50862E-06 1.40020E-06  
 1.29951E-06 1.20621E-06 1.11948E-06 1.03903E-06 9.64278E-07  
 8.94961E-07 8.30770E-07 7.71422E-07 7.16083E-07 6.64724E-07  
 6.16801E-07 5.72581E-07 5.31494E-07 4.93270E-07 4.57889E-07  
 4.25085E-07 3.94559E-07 3.66026E-07 3.39783E-07 3.15245E-07  
 2.92710E-07 2.71655E-07 2.52112E-07 2.33992E-07 2.17164E-07  
 2.01530E-07 1.87037E-07 1.73572E-07 1.61073E-07 1.49493E-07  
 1.38709E-07 1.28724E-07 1.19452E-07 1.10834E-07 1.02848E-07  
 9.54587E-08 8.85546E-08 8.21926E-08 7.62571E-08 7.07524E-08  
 6.56457E-08 6.09098E-08 5.65163E-08 5.24357E-08 4.86423E-08  
 4.51332E-08 4.18809E-08 3.88568E-08 3.60317E-08 3.34362E-08  
 3.10112E-08 2.87860E-08 2.67033E-08 2.47714E-08 2.29803E-08  
 2.13199E-08 1.97793E-08 1.83471E-08 1.70202E-08 1.57909E-08  
 1.46469E-08

C \*\*\*\*

C \* MATERIAL CARDS \*

C \*\*\*\*

M1	9019.60c	-0.478400	20000.60c	-0.504600	
	25055.60c	-0.017000			\$TLD-400
C	1100-A1	(soft A1)			
M2	13027.60c	0.9920	14000.60c	4.8214e-3	
	25055.60c	2.4648e-4	26054.60c	1.4306e-4	

```

26056.60c 2.2239e-3 26057.60c 5.0919e-5
26058.60c 6.7892e-6 29063.60c 3.5375e-4
29065.60c 1.5767e-4 $Al equilibrator
C ****
C * NEUTRON TALLIES *
C ****
F6:N 100
FM6 1.602E-08
FC6 Neutron Dose [Rad(TLD)/Src-Neutron]
C
F24:N 100
FC24 Neutron Fluence in TLD [Neutrons/cm^2/Src-Neutron]
C
F34:N 200
FC34 Neutron Fluence in Al [Neutrons/cm^2/Src-Neutron]
F74:N 100
FC74 Effective Neutron Kerma in TLD-400
E74 1.05000E-10 1.10000E-10 1.15000E-10 1.20000E-10
     1.27500E-10 1.35000E-10 1.42500E-10 1.50000E-10 1.60000E-10
     1.70000E-10 1.80000E-10 1.90000E-10 2.00000E-10 2.10000E-10
     2.20000E-10 2.30000E-10 2.40000E-10 2.55000E-10 2.70000E-10
     2.80000E-10 3.00000E-10 3.20000E-10 3.40000E-10 3.60000E-10
     3.80000E-10 4.00000E-10 4.25000E-10 4.50000E-10 4.75000E-10
     5.00000E-10 5.25000E-10 5.50000E-10 5.75000E-10 6.00000E-10
     6.30000E-10 6.60000E-10 6.90000E-10 7.20000E-10 7.60000E-10
     8.00000E-10 8.40000E-10 8.80000E-10 9.20000E-10 9.60000E-10
     1.00000E-09 1.05000E-09 1.10000E-09 1.15000E-09 1.20000E-09
     1.27500E-09 1.35000E-09 1.42500E-09 1.50000E-09 1.60000E-09
     1.70000E-09 1.80000E-09 1.90000E-09 2.00000E-09 2.10000E-09
     2.20000E-09 2.30000E-09 2.40000E-09 2.55000E-09 2.70000E-09
     2.80000E-09 3.00000E-09 3.20000E-09 3.40000E-09 3.60000E-09
     3.80000E-09 4.00000E-09 4.25000E-09 4.50000E-09 4.75000E-09
     5.00000E-09 5.25000E-09 5.50000E-09 5.75000E-09 6.00000E-09
     6.30000E-09 6.60000E-09 6.90000E-09 7.20000E-09 7.60000E-09
     8.00000E-09 8.40000E-09 8.80000E-09 9.20000E-09 9.60000E-09
     1.00000E-08 1.05000E-08 1.10000E-08 1.15000E-08 1.20000E-08
     1.27500E-08 1.35000E-08 1.42500E-08 1.50000E-08 1.60000E-08
     1.70000E-08 1.80000E-08 1.90000E-08 2.00000E-08 2.10000E-08
     2.20000E-08 2.30000E-08 2.40000E-08 2.55000E-08 2.70000E-08
     2.80000E-08 3.00000E-08 3.20000E-08 3.40000E-08 3.60000E-08
     3.80000E-08 4.00000E-08 4.25000E-08 4.50000E-08 4.75000E-08
     5.00000E-08 5.25000E-08 5.50000E-08 5.75000E-08 6.00000E-08
     6.30000E-08 6.60000E-08 6.90000E-08 7.20000E-08 7.60000E-08
     8.00000E-08 8.40000E-08 8.80000E-08 9.20000E-08 9.60000E-08
     1.00000E-07 1.05000E-07 1.10000E-07 1.15000E-07 1.20000E-07
     1.27500E-07 1.35000E-07 1.42500E-07 1.50000E-07 1.60000E-07
     1.70000E-07 1.80000E-07 1.90000E-07 2.00000E-07 2.10000E-07
     2.20000E-07 2.30000E-07 2.40000E-07 2.55000E-07 2.70000E-07
     2.80000E-07 3.00000E-07 3.20000E-07 3.40000E-07 3.60000E-07
     3.80000E-07 4.00000E-07 4.25000E-07 4.50000E-07 4.75000E-07
     5.00000E-07 5.25000E-07 5.50000E-07 5.75000E-07 6.00000E-07
     6.30000E-07 6.60000E-07 6.90000E-07 7.20000E-07 7.60000E-07
     8.00000E-07 8.40000E-07 8.80000E-07 9.20000E-07 9.60000E-07
     1.00000E-06 1.05000E-06 1.10000E-06 1.15000E-06 1.20000E-06
     1.27500E-06 1.35000E-06 1.42500E-06 1.50000E-06 1.60000E-06
     1.70000E-06 1.80000E-06 1.90000E-06 2.00000E-06 2.10000E-06
     2.20000E-06 2.30000E-06 2.40000E-06 2.55000E-06 2.70000E-06
     2.80000E-06 3.00000E-06 3.20000E-06 3.40000E-06 3.60000E-06
     3.80000E-06 4.00000E-06 4.25000E-06 4.50000E-06 4.75000E-06
     5.00000E-06 5.25000E-06 5.50000E-06 5.75000E-06 6.00000E-06
     6.30000E-06 6.60000E-06 6.90000E-06 7.20000E-06 7.60000E-06
     8.00000E-06 8.40000E-06 8.80000E-06 9.20000E-06 9.60000E-06
     1.00000E-05 1.05000E-05 1.10000E-05 1.15000E-05 1.20000E-05
     1.27500E-05 1.35000E-05 1.42500E-05 1.50000E-05 1.60000E-05
     1.70000E-05 1.80000E-05 1.90000E-05 2.00000E-05 2.10000E-05
     2.20000E-05 2.30000E-05 2.40000E-05 2.55000E-05 2.70000E-05
     2.80000E-05 3.00000E-05 3.20000E-05 3.40000E-05 3.60000E-05
     3.80000E-05 4.00000E-05 4.25000E-05 4.50000E-05 4.75000E-05
     5.00000E-05 5.25000E-05 5.50000E-05 5.75000E-05 6.00000E-05
     6.30000E-05 6.60000E-05 6.90000E-05 7.20000E-05 7.60000E-05
     8.00000E-05 8.40000E-05 8.80000E-05 9.20000E-05 9.60000E-05
     1.00000E-04 1.05000E-04 1.10000E-04 1.15000E-04 1.20000E-04
     1.27500E-04 1.35000E-04 1.42500E-04 1.50000E-04 1.60000E-04
     1.70000E-04 1.80000E-04 1.90000E-04 2.00000E-04 2.10000E-04
     2.20000E-04 2.30000E-04 2.40000E-04 2.55000E-04 2.70000E-04
     2.80000E-04 3.00000E-04 3.20000E-04 3.40000E-04 3.60000E-04
     3.80000E-04 4.00000E-04 4.25000E-04 4.50000E-04 4.75000E-04
     5.00000E-04 5.25000E-04 5.50000E-04 5.75000E-04 6.00000E-04

```





```

3.190883E-12 2.317993E-12 2.073727E-12 2.342736E-12 2.906890E-12
3.357531E-12 3.583292E-12 3.479792E-12 3.324279E-12 3.193020E-12
3.395974E-12 4.226197E-12 4.196578E-12 3.889959E-12 3.651716E-12
4.548008E-12 5.494937E-12 5.427950E-12 5.475872E-12 6.702588E-12
7.521065E-12 7.794732E-12 9.230063E-12 1.166246E-11 1.392013E-11
1.592826E-11 1.815352E-11 2.104696E-11 2.398644E-11 2.711052E-11
3.054031E-11 3.397492E-11 3.754370E-11 4.126886E-11 4.478367E-11
4.817058E-11 5.239371E-11 5.665689E-11 6.090929E-11 6.509596E-11
6.927147E-11 7.344699E-11 7.762251E-11 8.179814E-11 8.621534E-11
9.086275E-11 9.551016E-11 1.001576E-10 1.049809E-10 1.106255E-10
1.162924E-10 1.211196E-10 1.257221E-10 1.303245E-10 1.349269E-10
1.395293E-10 1.441317E-10 1.487371E-10 1.536074E-10 1.586503E-10
1.636932E-10 1.687362E-10 1.737791E-10 1.788220E-10 1.838650E-10
1.889079E-10 1.939508E-10 1.989937E-10 2.037815E-10 2.080533E-10
2.123108E-10 2.165683E-10 2.208258E-10 2.250833E-10 2.293408E-10
2.335983E-10 2.378558E-10 2.421131E-10 2.463106E-10 2.499054E-10
2.533428E-10 2.567804E-10 2.602180E-10 2.636554E-10 2.670928E-10
2.705303E-10 2.739677E-10 2.769811E-10 2.785762E-10 2.800564E-10
2.815367E-10 2.830170E-10 2.844973E-10 2.859776E-10 2.874578E-10
2.889381E-10 2.904184E-10 2.918987E-10 2.933790E-10 2.948592E-10
2.963364E-10 2.976287E-10 2.988118E-10 2.999949E-10 3.011780E-10
3.023611E-10 3.035442E-10 3.047274E-10 3.058613E-10 3.053862E-10
3.041371E-10 3.028881E-10 3.016391E-10 3.003901E-10 2.991410E-10
2.978920E-10 2.966430E-10 2.953940E-10 2.941449E-10 2.928959E-10
2.916469E-10 2.894781E-10 2.858629E-10 2.822294E-10 2.785958E-10
2.749622E-10 2.713335E-10 2.683108E-10 2.657121E-10 2.631134E-10
2.605147E-10 2.579161E-10 2.553180E-10 2.530240E-10 2.509704E-10
2.489169E-10 2.468633E-10 2.448097E-10 2.427561E-10 2.412816E-10
2.412176E-10 2.412173E-10 2.412170E-10 2.412167E-10 2.412164E-10
2.412162E-10 2.412159E-10 2.412155E-10 2.412153E-10 2.412149E-10
2.412147E-10 2.412143E-10 2.412140E-10 2.412138E-10 2.412135E-10
2.412132E-10 2.412129E-10 2.412126E-10 2.412123E-10 2.412120E-10
2.412117E-10 2.412114E-10 2.412111E-10 2.412108E-10 2.412105E-10
2.412102E-10 2.412099E-10 2.412096E-10 2.412093E-10 2.412090E-10
2.412087E-10 2.412084E-10 2.412081E-10 2.412078E-10 2.412076E-10
2.412072E-10 2.412069E-10 2.412067E-10 2.412063E-10 2.412061E-10
2.412057E-10 2.412054E-10 2.412052E-10 2.412049E-10 2.412046E-10
2.412043E-10 2.412040E-10 2.412037E-10 2.412034E-10 2.412031E-10
2.412028E-10 2.412025E-10 2.412022E-10 2.412019E-10 2.412016E-10
2.412013E-10 2.412010E-10 2.412007E-10 2.412004E-10 2.412001E-10

C ****
C * PHOTON TALLIES *
C ****

F16:P 100
FM16 1.602E-08
FC16 Secondary Gamma Dose [Rad(TLD)/Src-Neutron]
C
F44:P 100
FC44 Secondary Gamma Fluence in TLD [Gamma/cm^2/Src-Neutron]
C
F54:P 200
FC54 Secondary Gamma Fluence in Al [Gamma/cm^2/Src-Neutron]
C
NPS 50000000
DBCN 12j 70917 6j

```

## APPENDIX B – MCNP4C3 Sample Input Deck for TLD Activation Dose from $\beta$ -Decay – $^{20}\text{F}$

```

Model of TLD-400 with Al Equilibrator for F-20 Beta Spectrum
C **** CELL CARDS ****
C *   CELL CARDS *
C **** -----
C C | Mat | Density | X-plane | Y-plane | Z-plane | Import- | Comment
C # | #  |          | L       R | L       R | B       T | ance   |
C -----+-----+-----+-----+-----+-----+
 100    1    -3.1000   -100           IMP:E=1 $TLD-400
 200    2    -2.7100    100    -200           IMP:E=1 $Al equil.
 300    0           200           IMP:E=0 $Void

C **** SURFACE CARDS ****
C *   SURFACE CARDS *
C **** -----
C Srf|Sym-| Dim-1 | Dim-2 | Dim-3 | Comment
C # |bol |          |          |          |
C -----+-----+-----+-----+
 100 rpp -0.15000 0.15000 -0.15000 0.15000
        -0.04445 0.04445           $TLD-400      (0.3x0.3x0.0889 cm)
 200 rpp -0.40000 0.40000 -0.40000 0.40000
        -0.27305 0.27305           $Al equilibrator (0.8x0.8x0.5461 cm)

C **** DATA CARDS ****
C *   DATA CARDS *
C **** -----
MODE E          $Beta transport
PHYS:E 100.0
C **** -----
C *   SOURCE CARDS *
C **** -----
SDEF SUR=0 CEL=100 AXS=0 0 1 ERG=D1 RAD=D2 EXT=D3 POS=0 0 0
C Energy distribution is from Browne and Firestone disregarding the
C betas below 100 keV
SI1  0.100  0.300  0.600  1.300  2.500  5.000
  5.395
SP1  0.0000 0.00912 0.02596 0.12127 0.35179 0.48910
  0.00276
SI2  0  0.15
SI3  0.04445
C **** -----
C *   MATERIAL CARDS *
C **** -----
M1    9000.02p 0.643333 20000.02p 0.321667
      25000.02p 0.035000           $TLD-400
C 1100-Al (soft Al)
M2    13000.02p 0.9920    14000.02p 4.8214e-3
      25000.02p 2.4648e-4 26000.02p 2.4247e-3
      29000.02p 5.1142e-4           $Al equilibrator
C **** -----
C *   ELECTRON TALLIES *
C **** -----
*F18:E 100
FC18 Energy Deposited [MeV/Src-Beta]
C
NPS 50000
PRINT 10
PRDMP 1j -100 0 2

```

## APPENDIX C – MCNP4C3 Sample Input Deck for TLD Activation Dose from Delayed $\gamma$ 's After $\beta$ -Decay – $^{20}\text{F}$

```

Model of TLD-400 with Al Equilibrator for F-19 Decay Gamma Spectrum
C **** CELL CARDS ****
C * CELL CARDS *
C -----
C C | Mat | Density | X-plane | Y-plane | Z-plane | Import- | Comment
C # | # | | L R | L R | B T | ance |
C -----
 100   1    -3.1000   -100          IMP:P=1 $TLD-400
 200   2    -2.7100    100    -200          IMP:P=1 $Al equil.
 300   0           200          IMP:P=0 $Void

C **** SURFACE CARDS ****
C * SURFACE CARDS *
C -----
C Srf|Sym-| Dim-1 | Dim-2 | Dim-3 | Comment
C # | bol| | | |
C -----
 100 rpp -0.15000 0.15000 -0.15000 0.15000
        -0.04445 0.04445      $TLD-400          (0.3x0.3x0.0889 cm)
 200 rpp -0.40000 0.40000 -0.40000 0.40000
        -0.27305 0.27305      $Al equilibrator (0.8x0.8x0.5461 cm)

C **** DATA CARDS ****
C * DATA CARDS *
C -----
MODE P                               $Decay gamma transport
PHYS:P 100.0
C **** SOURCE CARDS ***
C *****
SDEF SUR=0 CEL=100 AXS=0 0 1 ERG=D1 RAD=D2 EXT=D3 POS=0 0 0
C Energy distribution is from Browne and Firestone
SI1  L  1.633602 3.332540
SP1  D  0.999910 0.000090
SI2  O  0.15
SI3  O 0.04445
C *****
C * MATERIAL CARDS *
C *****
M1    9000.02p 0.643333 20000.02p 0.321667
      25000.02p 0.035000                                $TLD-400
C 1100-Al (soft Al)
M2    13000.02p 0.9920     14000.02p 4.8214e-3
      25000.02p 2.4648e-4 26000.02p 2.4247e-3
      29000.02p 5.1142e-4                                $Al equilibrator
C *****
C * ELECTRON TALLIES *
C *****
F16:P 100
C FM card is 1.602E-08*1.00009
C There are 1.00009 gammas per beta decay
FMI16 1.602144e-8
FC16 Decay Gamma Dose [Rad(TLD)/Beta Decay]
C
NPS    20000000
PRINT  10
PRDMP  1j -100 0 2

```

## APPENDIX D – MCNP4C3 Sample Input Deck for TLD Activation Dose from Internal Bremsstrahlung After $\beta$ -Decay – $^{20}\text{F}$

```

Model of TLD-400 with Al Equilibrator for F-20 IB Spectrum
C **** CELL CARDS ****
C *   CELL CARDS *
C **** ****
C ---+---+---+---+---+---+---+
C C | Mat | Density | X-plane | Y-plane | Z-plane | Import- | Comment
C # | #  |        | L      | R      | L      | R      | B      | T      | ance
C ---+---+---+---+---+---+---+
 100   1    -3.1000   -100          IMP:P=1 $TLD-400
 200   2    -2.7100    100    -200          IMP:P=1 $Al equil.
 300   0     200          IMP:P=0 $Void

C **** SURFACE CARDS ****
C *   SURFACE CARDS *
C **** ****
C ---+---+---+---+---+---+
C Srf|Sym-| Dim-1 | Dim-2 | Dim-3 | Comment
C # |bol |        |        |        |
C ---+---+---+---+---+---+
 100 rpp -0.15000 0.15000 -0.15000 0.15000
      -0.04445 0.04445           $TLD-400          (0.3x0.3x0.0889 cm)
 200 rpp -0.40000 0.40000 -0.40000 0.40000
      -0.27305 0.27305           $Al equilibrator (0.8x0.8x0.5461 cm)

C **** DATA CARDS ****
C *   DATA CARDS *
C **** ****
MODE P           $Decay gamma transport
PHYS:P 100.0
C **** ****
C *   SOURCE CARDS *
C **** ****
SDEF SUR=0 CEL=100 AXS=0 0 1 ERG=D1 RAD=D2 EXT=D3 POS=0 0 0
C Energy distribution is from Browne and Firestone
S1I 0.001 0.010 0.020 0.040 0.100 0.300 0.600 1.300 2.500
    5.000 5.395
SP1 0.0000 0.0129 0.4500 0.4500 0.5800 0.6500 0.3500 0.3000 0.1450
    0.0340 4.8e-6
SI2 0 0.15
SI3 0.04445
C **** ****
C *   MATERIAL CARDS *
C **** ****
M1 9000.02p 0.643333 20000.02p 0.321667
    25000.02p 0.035000           $TLD-400
C 1100-Al (soft Al)
M2 13000.02p 0.9920 14000.02p 4.8214e-3
    25000.02p 2.4648e-4 26000.02p 2.4247e-3
    29000.02p 5.1142e-4           $Al equilibrator
C **** ****
C *   ELECTRON TALLIES *
C **** ****
F16:P 100
C FM card is 1.602E-08*0.029379
C There are 0.029379 IB per beta decay
FM16 4.7065235E-10
FC16 Internal Bremsstrahlung Dose [Rad(TLD)/Beta Decay]
C
NPS 20000000
PRINT 10
PRDMMP 1j -100 0 2

```

## APPENDIX E – MCNP4C3 Sample Input Deck for Aluminum Activation Dose from $\beta$ -Decay – $^{28}\text{Al}$

```

Beta Energy Deposited in TLD from Activated Al6061 (Al-28)
C **** CELL CARDS ****
C *   CELL CARDS *
C **** -----
C C | Mat | Density | X-plane | Y-plane | Z-plane | Import- | Comment
C # | #  |        | L      R | L      R | B      T | ance   |
C -----+-----+-----+-----+-----+-----+
 100    1    -3.1000   -100          IMP:E=1 $TLD-400
 200    2    -2.7100    100    -200          IMP:E=1 $Al equil.
 300    0           200          IMP:E=0 $Void

C **** SURFACE CARDS ****
C *   SURFACE CARDS *
C **** -----
C Srf|Sym-| Dim-1 | Dim-2 | Dim-3 | Comment
C # |bol |        |        |        |
C -----+-----+-----+-----+
 100 rpp -0.15000 0.15000 -0.15000 0.15000
          -0.04445 0.04445          $TLD-400          (0.3x0.3x0.0889 cm)
 200 rpp -0.40000 0.40000 -0.40000 0.40000
          -0.27305 0.27305          $Al equilibrator (0.8x0.8x0.5461 cm)

C **** DATA CARDS ****
C *   DATA CARDS *
C **** -----
MODE E          $Beta transport
PHYS:E 100.0
C **** -----
C *   SOURCE CARDS *
C **** -----
SDEF SUR=0 CEL=200 AXS=0 0 1 ERG=D1 RAD=D2 EXT=D3 POS=0 0 0
C Energy distribution is from Browne and Firestone disregarding the
C betas below 100 keV
SI1  0.100  0.300  0.600  1.300  2.500  2.863
SP1  0.0000 0.04294 0.10912 0.38395 0.45267 0.01132
SI2  0.15   0.40
SI3  0.27305
C **** -----
C *   MATERIAL CARDS *
C **** -----
M1    9000.02p 0.643333 20000.02p 0.321667
      25000.02p 0.035000          $TLD-400
C 1100-Al (soft Al)
M2    13000.02p 0.9920   14000.02p 4.8214e-3
      25000.02p 2.4648e-4  26000.02p 2.4247e-3
      29000.02p 5.1142e-4          $Al equilibrator

C **** -----
C *   ELECTRON TALLIES *
C **** -----
*F18:E 100
FC18 Energy Deposited [MeV/Src-Beta]
C
NPS 50000
PRINT 10
PRDMR 1j -100 0 2
DBCN 12j 14333 6j

```

## APPENDIX F – MCNP4C3 Sample Input Deck for Aluminum Activation Dose from Delayed $\gamma$ 's After $\beta$ -Decay – $^{28}\text{Al}$

```

Model of TLD-400 with Al Equilibrator for Al-28 Decay Gamma Spectrum
C **** CELL CARDS ****
C *      CELL CARDS *
C -----
C C | Mat | Density | X-plane | Y-plane | Z-plane | Import- | Comment
C # | # |          | L   R | L   R | B   T | ance   |
C -----
100  1    -3.1000   -100           IMP:P=1 $TLD-400
200  2    -2.7100    100   -200       IMP:P=1 $Al equil.
300  0        200           IMP:P=0 $Void

C **** SURFACE CARDS ****
C *      SURFACE CARDS *
C -----
C Srf|Sym-| Dim-1 | Dim-2 | Dim-3 | Comment
C # | bol|          |       |       |
C -----
100  rpp  -0.15000 0.15000  -0.15000 0.15000
      -0.04445 0.04445           $TLD-400      (0.3x0.3x0.0889 cm)
200  rpp  -0.40000 0.40000  -0.40000 0.40000
      -0.27305 0.27305           $Al equilibrator (0.8x0.8x0.5461 cm)

C **** DATA CARDS ****
C *      DATA CARDS *
C -----
MODE P          $Decay gamma transport
PHYS:P 100.0
C **** SOURCE CARDS ***
C *      SOURCE CARDS *
C -----
SDEF SUR=0 CEL=200 AXS=0 0 1 ERG=1.778988 RAD=D2 EXT=D3 POS=0 0 0
C Energy distribution is from Browne and Firestone
SI2  0.15 0.40
SI3  0.27305
C **** MATERIAL CARDS ***
C *      MATERIAL CARDS *
C -----
M1    9000.02p 0.643333 20000.02p 0.321667
      25000.02p 0.035000           $TLD-400
C  1100-Al (soft Al)
M2    13000.02p 0.9920    14000.02p 4.8214e-3
      25000.02p 2.4648e-4 26000.02p 2.4247e-3
      29000.02p 5.1142e-4           $Al equilibrator
C **** ELECTRON TALLIES ***
C *      ELECTRON TALLIES *
C -----
F16:P 100
C FM card is 1.602E-08*1.000
C There are 1.000 gammas per beta decay
FM16 1.602E-8
FC16 Decay Gamma Dose [Rad(TLD)/Beta Decay]
C
C
NPS    20000000
PRINT 10
PRDMR 1j -100 0 2

```

## APPENDIX G – MCNP4C3 Sample Input Deck for TLD Activation Dose from Internal Bremsstrahlung After $\beta$ -Decay – $^{28}\text{Al}$

```

IB Energy Deposited in TLD from Activated Al6061 (Al-28)
C **** CELL CARDS ****
C * CELL CARDS *
C -----
C C | Mat | Density | X-plane | Y-plane | Z-plane | Import- | Comment
C # | # | | L R | L R | B T | ance |
C -----
 100   1    -3.1000   -100           IMP:P=1 $TLD-400
 200   2    -2.7100    100    -200           IMP:P=1 $Al equil.
 300   0        200           IMP:P=0 $Void

C **** SURFACE CARDS ****
C * SURFACE CARDS *
C -----
C Srf|Sym-| Dim-1 | Dim-2 | Dim-3 | Comment
C # | bol|       |       |       |
C -----
 100 rpp -0.15000 0.15000 -0.15000 0.15000
          -0.04445 0.04445      $TLD-400      (0.3x0.3x0.0889 cm)
 200 rpp -0.40000 0.40000 -0.40000 0.40000
          -0.27305 0.27305      $Al equilibrator (0.8x0.8x0.5461 cm)

C **** DATA CARDS ****
C * DATA CARDS *
C MODE P           $IB transport
PHYS:P 100.0
C * SOURCE CARDS *
C *****
SDEF SUR=0 CEL=200 AXS=0 0 1 ERG=D1 RAD=D2 EXT=D3 POS=0 0 0
C Energy distribution is from Browne and Firestone
SI1  0.001  0.010  0.020  0.040  0.100  0.300  0.600  1.300  2.500
     2.863
SP1  0.0000 0.0800 0.3000 0.2900 0.3700 0.3800 0.1800 0.1140 0.0200
     3.1e-5
SI2  0.15  0.40
SI3  0.27305
C **** MATERIAL CARDS ****
C * MATERIAL CARDS *
C *****
M1    9000.02p 0.643333 20000.02p 0.321667
      25000.02p 0.035000      $TLD-400
C 1100-Al (soft Al)
M2    13000.02p 0.9920 14000.02p 4.8214e-3
      25000.02p 2.4648e-4 26000.02p 2.4247e-3
      29000.02p 5.1142e-4      $Al equilibrator

C *****
C * PHOTON TALLIES *
C *****
F16:P 100
C FM card is 1.602E-08*0.01734031
C There are 0.01734031 IB per beta decay
FM16 2.777918E-10
FC16 Internal Bremsstrahlung Dose [Rad(TLD)/Beta Decay]
C
NPS 20000000
PRINT 10
PRDMP 1j -100 0 2

```

## **DISTRIBUTION:**

MS 1146 K. O. Reil, 6423 (1)  
MS 1179 J. R. Lee, 15340 (1)  
MS 1142 J. W. Bryson, 6431 (1)  
MS 1142 R. A. Farmer, 6431 (1)  
MS 1142 M. J. Burger, 6431 (1)  
MS 1142 L. E. Martin, 6431 (1)  
MS 1142 J. T. Ford, 6431 (1)  
MS 1142 R. S. Domingues, 6431 (1)  
MS 1142 L. L. Lippert, 6431 (1)  
MS 1142 R. D. Gomez, 6431 (1)  
MS 1142 R. D. Beets, 6431 (1)  
MS 1179 D. E. Beutler, 15341 (1)  
MS 1179 R. J. Hohlfelder, 15341 (1)  
MS 0744 D. B. King 6424 (1)  
MS 1136 D. W. Vehar, 6433 (1)  
MS 1141 E. J. Parma, 6424 (1)  
MS 1146 A. J. Suo-Anttila, 6423 (1)  
MS 1146 P. J. Cooper, 6423 (1)  
MS 1146 K. R. DePriest, 6423 (15)  
MS 1146 P. J. Griffin, 6423 (1)  
MS 1146 S. M. Luker 6423 (1)  
MS 1146 G. A. Harms 6423 (1)  
MS 9018 Central Technical Files,  
8945-1 (1)  
MS 0899 Technical Library, 9616 (2)  
MS 0612 Review & Approval Desk,  
9612, (1) (for DOE/OST)

Dr. Leslie A. Braby (1)  
Texas A&M University  
Department of Nuclear Engineering  
3133 TAMU  
College Station, TX 77843-3133

Dr. John R. Ford, Jr. (1)  
Texas A&M University  
Department of Nuclear Engineering  
3133 TAMU  
College Station, TX 77843-3133

Dr. Ian S. Hamilton (1)  
Texas A&M University  
Department of Nuclear Engineering  
3133 TAMU  
College Station, TX 77843-3133

Dr. John G. Williams (1)  
Director, Nuclear Reactor Laboratory  
Engineering Building (20)  
University of Arizona  
P. O. Box 210020  
Tucson, AZ 85721-0020

Dr. Craig R. Heimbach (1)  
Aberdeen Test Center  
STECS-RS, Bldg. 860  
Aberdeen PG, MD 21005-5059

Dr. David M. Gilliam (1)  
NIST  
REACT/A-106  
Gaithersburg, MD 20899

Dr. T. Michael Flanders (1)  
Reactor Physics Division  
STEWS DT R  
WSMR, NM 88002-5158

Dr. James M. Adams (1)  
Building 235/A156  
NIST  
Gaithersburg, MD 20899

Ms. Mary Helen Sparks (1)  
Reactor Physics Division  
STEWS-NR-AT-R  
WSMR, NM 88002-5158